

IV.3 The Hybrid Performance Project (Hyper)

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Objectives

- Identify issues associated with the integration of high-temperature fuel cells and gas turbine cycles, and improve overall understanding of system limits and dynamic operability.
- Establish a viable control strategy for start-up of a fuel cell gas turbine hybrid power system.
- Propose control strategies for fuel cell gas turbine hybrids that minimize system impact and maximize system efficiency, and characterize the limits of operation for these strategies.
- Embed a fuel cell model that operates in real time into the control platform of the Hyper facility for hardware-in-the-loop simulation.

Approach

- Test the use of compressor bleed as a means to increase surge margin and decrease cathode air flow during startup.
- Test the use of cold air by-pass during startup and compare to the compressor bleed case for efficacy.
- Evaluate the impact of ramp rate of system startup on compressor surge margin.
- Evaluate the limits of operation for both bleed air and cold air by-pass as methods for managing air flow and energy during transient operation.
- Reduce a higher-order solid oxide fuel cell model to lumped parameter for operation in real time on the Atlas controller.
- Make use of expertise from Woodward Industrial Controls to accomplish the integration of the fuel cell numerical simulation with the Hyper facility hardware.

Accomplishments

- The use of compressor bleed was found to be an effective means of mitigating compressor surge and stall during startup. The maximum air flow diverted from the fuel cell cathode was equal to 18.5% of the compressor inlet flow.
- The results of the experiments using compressor bleed as a means of controlling system startup were presented at the ASME Turbo Expo in June of this year and were published in the proceedings.
- The use of cold air by-pass was also found to be an effective means of increasing surge margin during system startup. The maximum air flow diverted from the fuel cell cathode was equal to 50.2% of the compressor inlet flow.
- The use of cold air by-pass during startup resulted in significantly reduced fuel requirements and turbine inlet temperatures. Maximum fuel flows during startup using cold air by-pass were 22.8 g/s, while an equivalent compressor bleed required 32.4 g/s. A similar improvement was seen in maximum turbine inlet temperatures, 753°C for cold air by-pass and 1045°C for the use of compressor bleed. The results indicate

that cold air by-pass in a hybrid system is superior to compressor bleed in minimizing impact to both the fuel cell and turbine in the hybrid system.

- Experiments to parametrically vary the turbine acceleration ramp rate during startup are currently underway. Preliminary results indicate that the turbine acceleration ramp rate in a hybrid system is far more critical than in a simple cycle turbine.
- The steady-state limits of operation were evaluated for both compressor bleed and cold air by-pass. Cold air by-pass was found to have a greater range of operability, since the valve could be opened to 100%. Compressor bleed was limited by turbine exhaust gas temperature limits to 22.9% of compressor inlet flow, while 61.7% of the compressor inlet flow could be by-passed using cold air by-pass. Similarly, while no appreciable change in system pressure drop was observed for any use of compressor bleed, the total system pressure drop was reduced from 13.6% to 4.2% using cold air by-pass. The two control methods were shown to be complimentary. The results of these experiments were presented at the ASME Power conference in April of this year and published in the proceedings.
- A real-time fuel cell model has been developed and tested. It was successfully integrated into the Hyper facility control platform. The facility now has the capability of simulating fuel cell transients and evaluating fuel cell impact during transient operation of the system using a hardware-in-the-loop approach.
- System testing revealed considerable issues with regard to the manifolding of parallel heat exchangers. These issues are expected to translate to the manifolding of parallel fuel cell stacks.

Future Directions

- Fuel cell transients will be evaluated for both open and closed loop scenarios.
- The use of hot air by-pass as a control strategy will be evaluated and compared to compressor bleed and cold air by-pass.
- The application of the control strategies developed in previous studies to load transients will be evaluated.
- Numerical and hardware simulations will be conducted to quantify the magnitude of flow imbalance in the heat exchangers in the Hyper facility. The work will lead to the development of control strategies for balancing flow in parallel fuel cell systems in a pressurized environment.

Introduction

Hybrid fuel cell turbine power systems have been identified by the U.S. Department of Energy's National Energy Technology Laboratory (NETL) as a key technology in reaching high efficiencies and low emissions in future power generation [1]. The Hybrid Performance Project (Hyper) facility has been commissioned by the Office of Science, Technology, and Analysis at NETL to examine fundamental issues related to the dynamic operability of fuel cell gas turbine hybrid systems. The facility is made available for public research collaboration with universities, industry and other research institutions. The Hyper project research objectives have been described in some detail previously, but begin with the simulation of a direct-fired solid oxide fuel cell (SOFC) gas turbine (GT) hybrid system using a hardware-in-the-loop approach [2]. The

experimental facility at NETL makes use of a natural gas burner controlled by a real-time fuel cell model to simulate the thermal output of a solid oxide fuel cell. Pressure vessels, used for simulating the cathode and post combustion volumes, and exhaust gas recuperators are integrated into the system with a modified turbine and compressor on a single shaft.

The potential of SOFC/GT hybrids has led to the evaluation of a project utilizing a recuperated cycle developed under the U.S. DOE Advanced Turbine Program in an SOFC hybrid [3]. Experimental efforts in pressurized, direct-fired SOFC/GT hybrids have provided insight to steady-state operation and efficiency [4]. However, dynamic performance evaluation of fuel cell turbine hybrids has been limited to numerical computer simulation [5-8]. While these studies have provided considerable insight into the dynamic nature of fuel cell turbine

hybrids, the addition of hardware into the simulation presents an opportunity to both validate model predictions and discover anomalies in dynamic system behavior that can not be adequately predicted by a computer model alone.

Approach

A compressor surge or stall could be catastrophic to the fuel cell in a hybrid system. The approach taken to study system startup was to parametrically vary the amount of bleed air or cold air by-pass used during a cold start, and compare the ramp data to the stall line of the compressor map. The results can be graphically compared to evaluate the impact of compressor bleed air flow on total surge margin during startup. A simplified process flow diagram is shown in Figure 1, and a picture of the facility is shown in Figure 2.

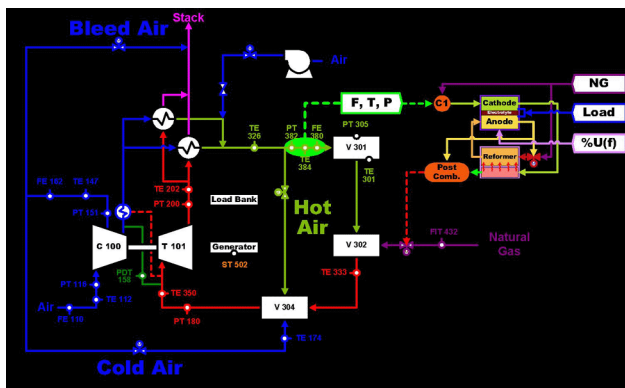


Figure 1. Simplified Flow Diagram for the Hybrid Simulation Facility at NETL



Figure 2. The Hybrid Performance Project Facility at NETL

The objective of the steady-state study was to identify potential methods for use in control strategies to regulate cathode air flow, absorb thermal transients, and mitigate risk of compressor stall and surge during operational transients. The change in system performance due to a change in by-pass flow was characterized in terms of the change in system air pressure drop and flow (air flow work) and change in input fuel flow rate. In order to separate various coupled phenomena, the work assumed a fixed fuel cell operation in spite of any change in cathode flow, and employed a fixed gas turbine generator output of no electrical load.

Results

A comparison is made in Figure 3 for the use of cold air by-pass and compressor bleed as strategies for managing air flow in a hybrid system. The data presented is the fuel required to divert air flow from the cathode, expressed in terms of percent of the fuel required for the case without any by-passed flow. Compressor bleed air is shown to have a much greater specific energy requirement, while cold air by-pass is shown to have an insignificant specific energy requirement over the same operable range of by-passed flow.

The huge increase in energy requirement shown for the case of compressor bleed indicates that it would be an effective means of absorbing a thermal transient impacting the turbine in the system. The data for the cold air by-pass shows that it would be

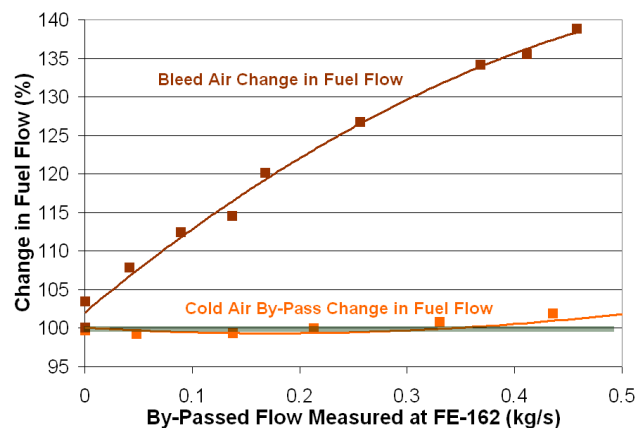


Figure 3. A Comparison of Percent Change in Fuel Required for Constant Turbine Speed as a Function of Air Flow Bled or By-Passed

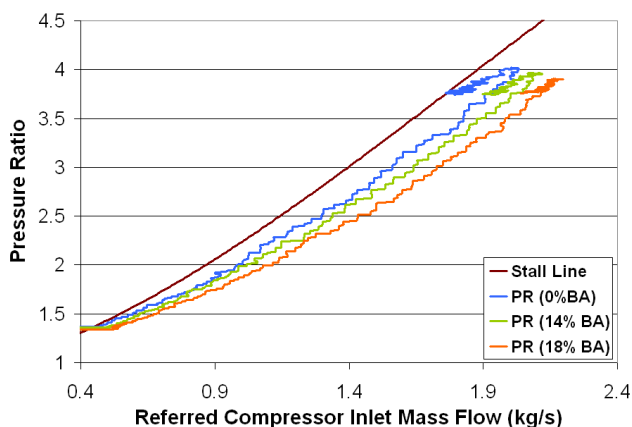


Figure 4. A Comparison of Startup Profiles for Three Bleed Air Cases to the Compressor Map Stall Line

an effective means of controlling cathode air flow without a significant penalty in system efficiency.

The studies performed using bleed air to increase compressor surge margin during startup are summarized for three different bleed air flow cases in Figure 4. The data are plotted with the stall line from the manufacturer's compressor map. The three cases plotted in the figure are 1) a valve setting of 0%, representing a case without compressor bleed; 2) a valve setting of 14%, representing a case with compressor bleed equivalent to 10.5% of the compressor inlet flow; and 3) a valve setting of 18%, representing a case with compressor bleed equivalent to 18.5% of the compressor inlet flow. The results can be used to illustrate how increasing compressor bleed air flow provides an increase in the operating surge margin during the startup.

Similar results were shown for the case of cold air by-pass, but with far less impact to the system. Turbine inlet temperatures were lower. System pressure drops were significantly decreased, and fuel requirements were substantially lower.

Conclusions

- Tests were conducted using the Hyper experimental facility at NETL to characterize the implementation of compressor bleed air and cold air by-pass as methods for manipulating hybrid system process variables through air flow management.

- For by-passed flows representing less than 25% of compressor inlet flow, cold air by-pass operation did not require any significant increase in energy.
- The cold air by-pass was also shown to be an effective method to increase the operating surge margin and avoid compressor stall.
- The use of compressor bleed air was found to be an effective method for increasing shaft load and absorbing thermal transients with reduced by-pass flow. This indicates potential for system control during fuel cell load loss or reduction.
- Compressor bleed air was also shown to be an effective means to increase the compressor surge margin. The method was limited because by-passed flows beyond 22% of compressor inlet air could not be sustained without exceeding the exhaust gas temperature (EGT) constraint.
- The data presented provide the first qualitative steps in characterizing possible control methods for hybrid fuel cell gas turbine power systems using compressed air flow management with valves only in cold-service side streams.
- The use of compressor bleed air and cold air by-pass simultaneously offer the potential for system control through a variety of transient scenarios.
- The methods studies show promise for effective control of a hybrid system without the direct intervention of isolation valves or check valves in the main pressure loop of the system, which introduce substantial pressure losses. The elimination of such measures for protection and control during transient operation would allow for the full potential efficiency of the hybrid system to be realized.
- Tests were conducted using the Hyper experimental facility at NETL to evaluate the use of compressor bleed air as a control strategy to avoid stall and surge during the initial startup of a solid oxide fuel cell turbine hybrid power system.
- The use of bleed air during startup was shown to be effective in increasing compressor mass flow and avoiding stall and surge during startup, and a base condition was established for future tests of other control strategies.

- The use of cold air by-pass during startup was shown to be effective in increasing compressor mass flow and avoiding stall and surge during startup with a significant reduction in system impact over compressor bleed.
- A real-time fuel cell model was successfully integrated into the control platform of the Hyper facility.

FY 2005 Publications/Presentations

1. Tucker, D.; Lawson, L. O.; Gemmen, R. S., "Evaluation of Hybrid Fuel Cell Turbine System Startup with Compressor Bleed," 2005 ASME Turbo Expo, GT2005-68784.
2. Tucker, D.; Lawson, L. O.; Gemmen, R. S., "Characterization of Air Flow Management and Control in a Fuel Cell Turbine Hybrid," Proceedings of the ASME Power Conference, April 2005, PWR2005-50127.

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2. Tucker, D.; Liese, E.; VanOsdol, J. G.; Lawson, L. O.; Gemmen, R. S., "Fuel Cell Gas Turbine Hybrid Simulation Facility Design," 2003 ASME International Mechanical Engineering Congress and Exposition, New Orleans, LA.
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4. Veyo, S. E.; Lundburg, W. L.; Vora, S. D.; Litzinger, K. P., "Tubular SOFC Hybrid Power System Status," Proceedings of the ASME Turbo Expo 2003, June 2003, GT2003-38943.
5. Costamagna, P.; Magistri, L.; Massardo, A. F., "Design and Part-Load Performance of a Hybrid System Based on a Solid Oxide Fuel Cell Reactor and a Micro Gas Turbine," *Journal of Power Sources*, Vol. 96, (2001), pp. 352-368.
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